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**ESTIMATING NET PRIMARY PRODUCTIVITY USING
SATELLITE AND ANCILLARY DATA**

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ABSTRACT

The net primary productivity (C) or the annual rate of carbon accumulation per unit ground area by terrestrial plant communities is the difference of gross photosynthesis (A_g) and respiration (R) per unit ground area. Available field observations show that R is a large and variable fraction of A_g , although it is generally recognized that there are considerable difficulties in determining these fluxes, and thus pose challenge in assessing the accuracy. Further uncertainties arise in extrapolating field measurements (which are acquired over a hectare or so area) to regional scale. Here, an approach is presented for determining these fluxes using satellite and ancillary data to be representative of ©2002 by the American Institute of Aeronautics and Astronautics, Inc. No copyright is asserted in the United States under Title 17, U.S. Code. The U.S. Government has a royalty-free license to exercise all rights under the copyright claimed herein for Government purposes. All other rights are reserved by the copyright holder.

regional scale and allow assessment of interannual variation. A_g has been expressed as the product of radiation use efficiency for gross photosynthesis by an unstressed canopy and intercepted photosynthetically active radiation, which is then adjusted for stresses due to soil water shortage and temperature away from optimum. R has been calculated as the sum of growth and maintenance components (respectively, R_g and R_m). The R_m has been determined from nitrogen content of plant tissue per unit ground area, while R_g has been obtained as a fraction of the difference of A_g and R_m . Results for five consecutive years (1986-1990) are presented for the Amazon-Tocontins, Mississippi, and Ob River basins.

INTRODUCTION

The net primary productivity or the rate of carbon accumulation by terrestrial plant communities per unit area (C) is the difference of gross photosynthesis by the canopy (A_g) and autotrophic respiration of the stand (R):

$$C = A_g - R \quad (1)$$

A rather attractive approach for determining C was proposed by Monteith (1977) as:

$$C = RUE * IPAR \quad (2)$$

where IPAR is the intercepted photosynthetically active radiation and RUE is the radiation use efficiency. This approach has been used to determine C at varied spatial scale (e.g., Ruimy et al., 1994).

Seasonal variation of A_g is determined primarily by IPAR and the maximum rate of photosynthesis by leaves (Monteith, 1977; Choudhury, 2000a), while seasonal variation of R is determined by changes of leaf, stem and root biomass and their specific respiration coefficients, and these coefficients have been observed to increase with tissue temperature (Choudhury, 2001a). Because of these differing sensitivities of A_g and R to biophysical factors, it is desirable to calculate these two fluxes separately.

MODELING AND INPUT DATA

Gross Photosynthesis

The approach used to determine A_g can be expressed as follows:

$A_g = RUE_g * IPAR * \Sigma_1(W) * \Sigma_2(T) \quad (3)$
where RUE_g is radiation use efficiency for gross photosynthesis by an unstressed canopy, and $\Sigma_1(W)$ and $\Sigma_2(T)$ are prescribed functions of available soil moisture (W) and foliage temperature (T). These functions account for stresses due to soil water deficit, and deviation of foliage temperature from the optimum range for photosynthesis.

Details about the calculation of A_g and input data requirements can be found in Choudhury (2000a), and briefly described here. The variation of photosynthesis by a leaf with irradiance has been described by a non-rectangular hyperbola. The maximum rate of leaf photosynthesis in this non-rectangular hyperbola depends upon the leaf nitrogen content, which varies within the canopy. The radiative transfer equation, with boundary condition of direct and

diffuse PAR incident on the canopy, is solved to obtain irradiance on leaves, and interception by the canopy. The single scattering albedo of the radiative transfer equation, which controls scattering of irradiance by leaves, also depends upon the nitrogen content of leaves. The sunlit leaves receive both direct and scattered irradiance, while shaded leaves receive only the scattered irradiance. The instantaneous canopy photosynthesis is obtained by numerically integrating photosynthesis by sunlit and shaded leaves weighted by their fractions at any depth within the canopy. The instantaneous intercepted PAR, and canopy photosynthesis are integrated at 15 min. interval throughout the day-light period considering diurnal variation of incident direct and diffuse PAR to obtain the daily total A_g for an unstressed canopy and IPAR. The available soil moisture needed to account for the effect of soil water stress on A_g has been determined by solving water and energy balance equations (Choudhury and DiGirolamo, 1998).

The input meteorological data (e.g., incident PAR, air temperature, precipitation) have been derived from radiances measured by sensors on board polar orbiting and geo-stationary satellites (e.g., NOAA, GOES), obtained as output of four dimensional data analysis (specifically the frictional velocity, needed to solve the energy balance equation) and as a merged product of ground observations and satellite-based measurements (specifically, precipitation used in the water balance calculations). The fractional interception of incident photosynthetically active radiation has been calculated from soil adjusted vegetation index (SAVI), which is determined from visible and near-infrared reflectance derived from measurements by the advanced very high resolution radiometer (AVHRR) on

board the NOAA satellites after correcting from sensor degradation and atmospheric affects on the satellite-observed radiances (Choudhury et al., 1994; Choudhury and DiGirolamo, 1998).

Respiration

Respiration (R) has been calculated according to the functional, two-compartment model of McCree (1974), as being the sum of growth and maintenance processes (denoted, respectively, as R_g and R_m). The R_g has been expressed as:

$$R_g = (1 - Y_G) \{ A_g - R_m \} \quad (4)$$

where Y_G is the growth conversion efficiency (i.e., mole of carbon synthesized per unit mole assimilated). Chemical composition of plant tissues determines the magnitude of Y_G and it is not directly affected by stress. A synthesis of the published values of Y_G for different plant species give 0.69 for woody vegetation (shrubs and trees) and 0.74 for herbaceous vegetation (natural grasses and crops), with a coefficient of variation of about 12%.

R_m has generally been observed to vary strongly with tissue temperature, and it has been expressed in terms of its value at a specified mean daily temperature (T_o , °C), namely, $R_m(T_o)$, as:

$$R_m(T) = R_m(T_o) Q_{10}^{(T-T_o)/10} I_0(\Delta T/2) \quad (5)$$

where Q_{10} is the temperature response coefficient (the value of which determines the magnitude of change in $R_m(T)$ due to 10°C change in temperature), $I_0(y)$ is the modified Bessel function of argument y , and ΔT is the diurnal range of tissue temperature. Observations give Q_{10} to be about 2.0 around 20°C, while it increases for lower, and decreases for higher temperature.

Available data for $R_m(T_o)$ at any prescribed T_o show much variability (more than a factor of three) for different tissues (roots, stem, and leaves) of a particular species, and this is also the

case for the same tissue for different species. Observations for different tissues and species analyzed by Ryan (1991) show that while $R_m(T_o)$ varied by three orders of magnitude, 58% of the variability of R_m can be explained as being due to the associated variability of the nitrogen content (N) of the tissue (as determined by linear regression analysis). Such a relationship between R_m and N can be reconciled by noting that protein turnover in plant tissues is considered to a major determinant of R_m . For a given nitrogen content, $R_m(T_o)$ has been observed to be about a factor two higher for roots as compared to that for leaves, which has been suggested to be due to the work done by roots to extract ions from soil. Observations also show that, for a given nitrogen content, $R_m(T_o)$ of leaves for species growing in boreal climate is about a factor of two higher than that for species growing in temperate climate, which has been suggested to be due to adaptation to growing in noticeably different temperature.

The equation for $R_m(T_o=20)$ (in units of mol CO₂ m⁻² d⁻¹) for species growing in a temperate region used in this study is:

$$R_m(T_o) = 0.21 (N_f + N_s + 2 N_r) \quad (6)$$

where N_f , N_s , and N_r are, respectively, the nitrogen content per unit ground area of live foliage, stem, and roots (mol N m⁻²). The first, second and the third term on the right hand side of Eq. (6) provides, respectively, maintenance respiration of foliage, stem and roots. As noted above, the cost of maintaining roots is higher than that for foliage.

The input data required for calculating R, in addition to those required for A_g , are the diurnal range of temperature plant tissues (ΔT) and L_o . In this study, ΔT has been approximated to be that for air temperature, which was determined by combining surface and satellite data. L_o has been determined from the AVHRR data.

RESULTS AND DISCUSSION

The results of calculations for 60 consecutive months (1986-1990) are presented in Table 1 for the Amazon, Mississippi, and Ob River basins. None of the model parameters have been determined by calibration against field measurements of these fluxes or to match fluxes. Respiration is calculated to be about 73%, 63%, and 66% of gross photosynthesis of these three river basins, respectively. Particularly noticeable is the interannual variation of two of the three river basins. Rather low gross photosynthesis of $60 \text{ mol C m}^{-2} \text{ yr}^{-1}$ was calculated for the Mississippi River basin for the year 1988, due largely to drought year for most of the basin. Maintenance respiration is calculated to be about 75% of total respiration. Representativeness of these results are being evaluated.

Table 1. Calculated Mean and Inter-annual Range of Carbon Balance Fluxes ($\text{mol C m}^{-2} \text{ yr}^{-1}$) for the Amazon, Mississippi, and Ob River basins for 1986-1990.

| | A_g | R | C |
|--------------------------|---------|---------|-------|
| Amazon River basin: | | | |
| Mean | 194 | 142 | 51 |
| Range | 187-200 | 140-146 | 49-59 |
| Mississippi River basin: | | | |
| Mean | 80 | 50 | 30 |
| Range | 60-89 | 47-52 | 13-37 |
| Ob River basin: | | | |
| Mean | 56 | 37 | 19 |
| Range | 51-64 | 30-40 | 13-26 |

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